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Article (Published Version)

International Journal of Disaster Risk Reduction 35 (2019) 101068

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Spatio-temporal changes in terrestrial water storage in the Himalayan river basins and risks to water security in the region: A review

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ARTICLE INFO

Keywords:
Himalayan river basins
Terrestrial water storage
Groundwater abstraction
Climate change
South Asia

ABSTRACT

Nearly one-fifth of the Earth's accessible freshwater is stored in the densely-populated, alluvial floodplains of the Brahmaputra, Ganges, Indus, Irrawaddy and Meghna River Systems in the Himalayan region where extreme hydrological conditions exist due to the seasonal variability in terrestrial water storage (TWS). Groundwater storage (GWS) – a hidden resource underneath the land surface, plays a critical role in sustaining irrigated agriculture in these river basins, particularly during the dry season when rice crops are generally grown in irrigated lands across South Asia. Although monitoring of groundwater levels has been operational in the region for a number of decades, a basin-wide comprehensive assessment of GWS is lacking in most river basins. The NASA's Gravity Recovery and Climate Experiment (GRACE) twin satellites offer an opportunity to map basin-wide changes in GWS where in-situ observations are limited in time and space. GRACE-derived assessments of GWS vary substantially in these basins and have not been reconciled with in-situ observations in most cases. Recent declining trends in GWS over the Himalayan river basins are attributed primarily to over-abstraction of groundwater due to dry-season irrigation. Seasonal variability in terrestrial water is likely to increase or become unpredictable in the future as a result of increased climate variability. The consequent impacts may potentially threaten the security of water supply and food in the region, where there is currently a growing demand for food grains from irrigated agriculture, energy, and domestic and industrial water supplies.

1. Introduction

Globally, freshwater represents ~2.5% of the Earth's total water content. Approximately 30% of this freshwater is stored as groundwater and the rest is stored in glaciers and ice caps (68.6%), snow and ice (0.95%), surface-water bodies (0.3%) (i.e., rivers, lakes and wetlands), soil (~0.05%), and atmosphere (~0.03%) [1]. The total groundwater volume in the upper 2-km of the Earth's surface is approximately 23 million km^3, of which < 5 million km^3 is modern (i.e., < 50 years old) [2]. Fresh groundwater and other individual freshwater stores combined with an additional 1% saline water store (i.e. saline lakes and groundwater) collectively represent the total terrestrial water storage (TWS) on the Earth's surface. TWS is an important part of the global hydrological cycle, and its changes through time and space, which demonstrate the dynamic nature of hydrological components, are often influenced by anthropogenic activities (e.g., groundwater withdrawal for irrigation) and climatic variations. In addition to growing demands for freshwater worldwide, climate extremes such as recurrent droughts and intensive rainfall events are expected to strongly influence TWS and regional water budgets, particularly in the Himalayan region [3–5].

Nearly one-fifth of the Earth's total freshwater storage can be found in the Himalayan region of southern Asia (Fig. 1) – home to some 1.7 billion people. Being located in the subtropical region, South Asian countries (here we refer to Bangladesh, Bhutan, India, Myanmar, Nepal, Pakistan and Sri Lanka) are generally characterised by abundant water resources. During the monsoon season (generally from June to September), surface water (i.e., water in river channels, wetlands and floodplains) is abundant throughout the region; during the dry season (generally from March to May), surface water is generally scarce. A vast amount of freshwater is stored as groundwater beneath the densely-populated floodplains of the Ganges, Brahmaputra, Meghna and Indus River systems [9]. In the dry season (prior to the wet monsoon season) or when the moisture-laden monsoon rainfall is delayed, this storage reaches its critical level. Groundwater is also considered to be a safer alternative to often-polluted surface water all year round. For these characteristics, groundwater is increasingly becoming the main source

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https://doi.org/10.1016/j.ijdrr.2019.101068
Received 16 January 2018; Received in revised form 16 January 2019; Accepted 16 January 2019
Available online 19 January 2019

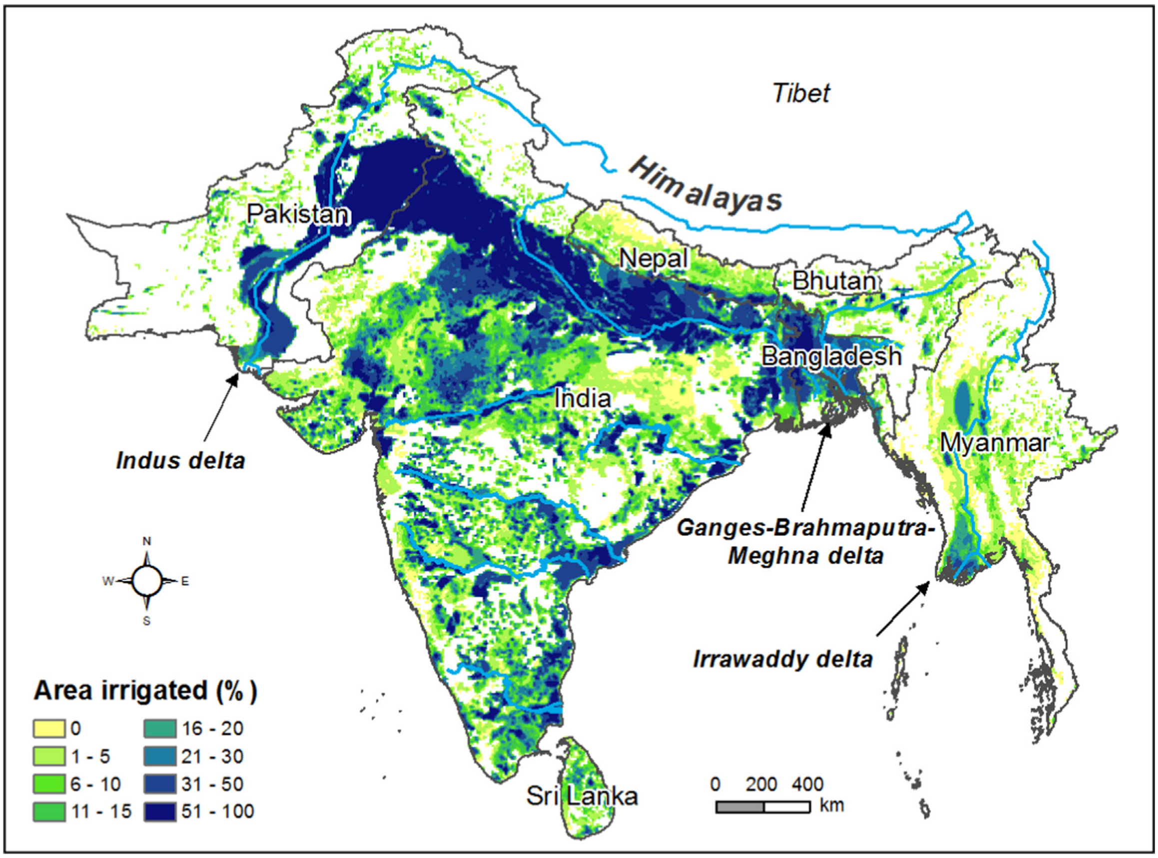

Fig. 1. Major Himalayan rivers and the general location of the river basins and mega deltas in South Asia. Information of land areas under irrigation (shown in colour shades) is taken from the digital global map of irrigation [38]. Areas under irrigation are shown as percentages of the land surface area.

of domestic, industrial and irrigation water supplies in the Himalayas and worldwide too. In many developing nations (e.g., Indian, Bangladesh), groundwater abstraction has accelerated resource (e.g. agricultural, industrial) development over the past 20 years and led to major social and economic benefits [6].

Groundwater-fed irrigation has become the mainstay of irrigated agriculture over much of India, Bangladesh, Pakistan (Punjab and Sindh provinces), Nepal (Terai plains) and Myanmar (Central Dry Zone) (see Fig. 2) [7,8]. Groundwater abstraction from the transboundary Indo-Gangetic Basin (also known as IGB) that stretches from Pakistan in the west to Bangladesh in the east and traverses the entire length of northern India comprises 25% of global groundwater withdrawals, sustaining irrigated agriculture in Pakistan, India, Nepal and Bangladesh [9]. Intensive and unsustainable use of groundwater in South Asia, particularly in northern India, Pakistan, and central and northwestern Bangladesh, has led to rapid depletion of groundwater storage in recent

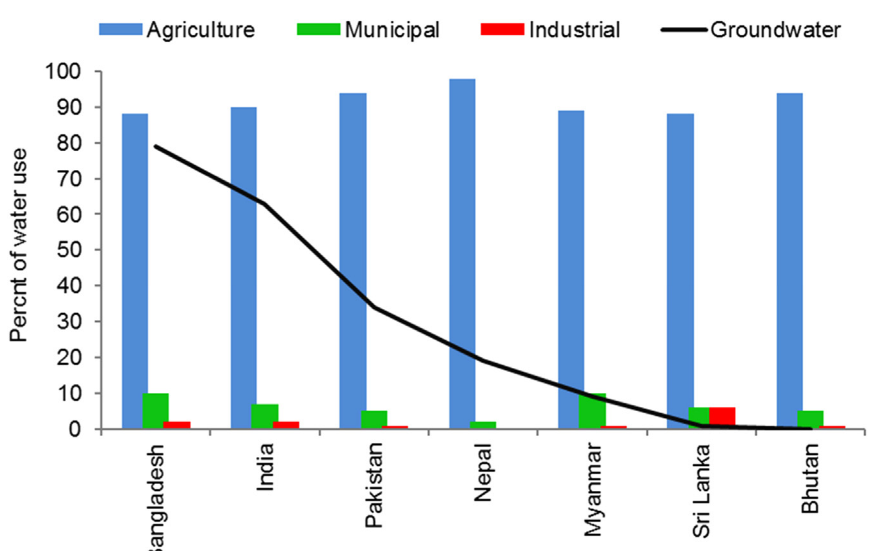

Fig. 2. Use of total freshwater and proportion of groundwater use in agricultural, industry and municipal sectors in seven South Asian countries (data source: FAO AQUASTAT 2016; http://www.fao.org/nr/water/aquastat/water_use/index.stm).

years. NASA's GRACE (Gravity Recovery and Climate Experiment) satellite observations have been used to show that the northern India has lost approximately 109 km^3 of groundwater between 2002 and 2008 [10,11]. Over the same period, India's neighbour Bangladesh, which has an equivalent of 4.5% of India's landmass, has depleted nearly 3 km^3 of its groundwater storage due to over-abstraction for dry-season rice cultivation [12]. It is reported that the long-term groundwater depletion has contributed substantially to global sea-level rise [13]; it's depletion in Asia is estimated to have contributed to a global sea-level rise of 2.2 mm over the period 2001–2008. Recent sea-level rise in the Bay of Bengal can be attributed, at least in part, to over-abstraction of groundwater to supply irrigation and municipal water over the last few decades [14].

Despite the importance of having reliable estimates of TWS, the knowledge about the spatial and temporal variations and its individual components is generally lacking. This is particularly true at large, global to regional scales due to the absence of any dedicated global-scale monitoring network of individual water stores (i.e., surface water, soil moisture, and groundwater). In this review, we synthesise recent reporting of long-term TWS changes in various river basins in the Himalayan region and provide a detailed picture of the recent changes in the TWS, and critically, the changes in groundwater storage that is vital for the sustainability of irrigated agriculture and food security in South and Southeast Asian river basins. In addition, we analyse precipitation and GRACE satellite datasets over the Himalayan river basins in order to provide an updated picture of changes in terrestrial water storage of the region.

2. River Basins in the Himalayan Region

There are a number of large river basins (Fig. 3) located in the Himalayan region that are collectively home to nearly 1 billion people (Table 1). These are the Ganges, Brahmaputra, Meghna, Indus and Irrawaddy River Basins all of which are sourced in the Himalayan or the Tibetan Plateau, and their hydrology is largely dependent on the Asian summer monsoonal rainfall and water supplies from the Himalayan glacier melting. In this review, we provide a detailed account of the Himalayan River Basins that is often missing in technical literature.

2.1. The Ganges-Brahmaputra-Meghna (GBM) River Basin

The Ganges-Brahmaputra-Meghna (GBM) River Basin is the largest river basin of the Himalayan region (Fig. 3). Three individual river basins, namely the Ganges, Brahmaputra and Meghna Rivers jointly form the GBM Basin that encompasses a significant part of India, China, Bangladesh, Nepal and Myanmar. The GBM Basin covers an area of approximately 1.7 million km^2 and has a population of about 700 million. The GBM River System is considered to be a transboundary one even though the three rivers of this system have distinct characteristics and flow through different regions within the Himalayas [15].

The GBM River System is the third largest freshwater outlet to the world's oceans following the Amazon and the Congo River systems [16]. The headwaters of both the Ganges and Brahmaputra rivers originate in the Himalayan Mountains. Originating from the high western Himalayas (Gangotri and Satopanth Glaciers), the Ganges River flows southwest into India and then turns southeast and flows through the entire length of the Indo-Gangetic Plain before entering Bangladesh from the west. Total length of the Ganges River is approximately 2600 km. The Ganges River is not braided in nature and is generally characterised by deep channelling with numerous channel bars through much of its course, particularly in the lower reach. The Ganges River in Bangladesh is known as the Padma that ultimately forms the confluence

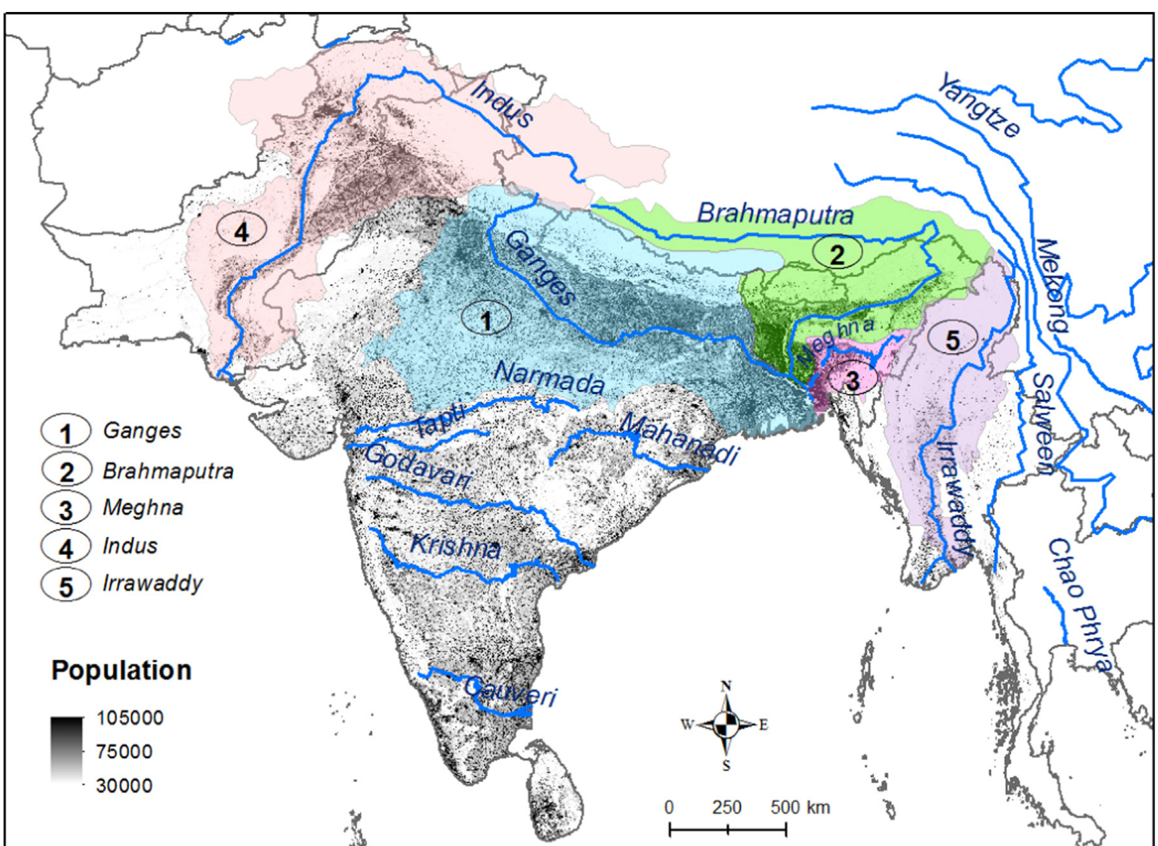

Fig. 3. Location of the major Himalayan river basins and other river in South Asia. Gridded population over Bangladesh, Bhutan, India, Myanmar, Nepal, Pakistan and Sri Lanka are shown in the background as grey shades (data source: LandScan Global Population Data 2007 from the OakRidge National Laboratory, USA).

Table 1
River basins in the Himalayan region and the countries where they are located along with the population living within the river basins.

Rivers	Basin Area (km^2)	Population	Country (% land area of each country)
Ganges	1,097,000	561,726,420	India (26), Bangladesh (33), China (< 1), Nepal (100),
Brahmaputra	539,410	102,744,980	India (6), Bangladesh (27), Bhutan (100), China (3)
Meghna	75,060	33,532,360	Bangladesh (24), India (1)
Indus	1,039,560	177,877,830	Afghanistan (11), China (1), India (14), Pakistan (65)
Irrawaddy	387,700	29,512,090	China (< 1), India (< 1), Myanmar (53)

with Brahmaputra (Jamuna) in central Bangladesh. The combined flow, known as the Padma River, flows toward the southeast and joins the Meghna River in the southeastern part of Bangladesh from where it turns south into the Bay of Bengal as the lower Meghna.

The Brahmaputra River is the largest transboundary river in the Himalayan region with a total length of approximately 2900 km. With its origin in the Angsi glacier, located on the northern side of the Himalayas in Tibet, the Brahmaputra River flows through southern Tibet (China) and breaks through the Himalayas in many great gorges. It eventually flows southwest through the Assam Valley and turns toward the south where it enters Bangladesh. In Bangladesh, the Brahmaputra River is known as Jamuna before merging with the Ganges (Padma) and Meghna rivers in central and southeastern Bangladesh. This course of the Brahmaputra (Jamuna) River is approximately 720 km within Bangladesh and throughout its course the river is mostly braided in nature with numerous channel bar formations [17].

The Meghna River originates in the hills of Shillong and Meghalaya of India. The main course is known as the Barak River, which has a considerable catchment in the ridge and valley terrains in eastern Assam State of India. On reaching the border with Bangladesh near Sylhet, the Barak River bifurcates into two separate courses – the Surma and the Kushiyara Rivers. The Surma flows to the north of Sylhet where several small rivers from the Khasia and Jaintia Hills of Shillong join the main course. These tributaries are locally deep and incised, and highly flashy (i.e., the hydrograph presents high peak discharge and steep rising and falling limbs) in nature and often generates flash floods. This region is the wettest place on Earth with an average annual rainfall of greater than 10,000 mm. The other branch of the Barak River, the Kushiyara, receives left bank tributaries from the Tripura Hills of eastern India (Tripura State). Both river courses (Surma and Kushiyara) re-join in north-central Bangladesh where the combined course forms the Meghna River. The Ganges (Padma) forms a confluence with the Meghna and their combined course ultimately flows into the Bay of Bengal as the lower Meghna. The total length of the river is nearly 930 km and, for the most part, the river is predominantly meandering in nature [8].

2.2. The Indus River Basin

The Indus River is a transboundary river system that flows through several countries – India, China, Afghanistan and Pakistan. The Indus River Basin (Fig. 3) covers a land area of ~1 million km^2 and encompasses various proportions of the total area of Pakistan (65%), India (14%), China (1%) and Afghanistan (11%) (Table 1). The Indus River Basin stretches from the Himalayan Mountains in the north to the dry alluvial plains of Sindh Province of Pakistan in the south and finally flows out into the Arabian Sea [8]. The total length of the river is approximately 3180 km (1976 miles) and the total basin area is about 1,039,560 km^2. The main branch of the Indus River runs through the Ladakh district of Jammu and Kashmir State of India and then enters the northern areas of Pakistan (Gilgit-Baltistan), flowing between the western Himalayan and Karakoram Mountains [18]. Along this reach of the river, discharge volume increases by a number of tributaries entering the main river from catchments in the Karakoram Mountains. Immediately north of the mountain Nanga Parbat, the westernmost peak of all the high peaks of the Himalayas, the Indus River turns in a southerly direction and flows along the entire length of Pakistan and ultimately merges into the Arabian Sea near the port city of Karachi in Sindh Province of Pakistan. Tributaries to this reach of the river from the western Himalayas are the Jhelum, Chenab, Ravi, and Sutlez Rivers, from the Indian states of Jammu, Kashmir and Himachal Pradesh, and the Kabul, Swat, and Chitral Rivers from the Hindu Kush Mountains.

2.3. The Irrawaddy River Basin

The Irrawaddy River Basin (Fig. 3) is located primarily in Myanmar (formerly known as Burma), which is drained by the Irrawaddy River (locally known as Ayeyarwady River) and its many tributaries in the north and distributaries in the south [8]. The Irrawaddy River is formed by the confluence of the Nmai and Mali Rivers. Both of these rivers rise from the Himalayan glaciers of the high and remote mountains in northern Myanmar. The eastern branch, the Nmai River rises from the Languela glacier on the border with Tibet (China) and is characterised by greater volume of discharge and a steep gradient. On the western side, the Mali River has a gentler topographic gradient. Irrawaddy River is the main waterway of Myanmar and is approximately 2170 km (1350 miles) long from its origin in the eastern Himalayas to the Andaman Sea in the south, after flowing through the vast plains of the Irrawaddy Delta. The largest tributary of the river is the Chindwin River that flows from the northwestern side of the basin and joins the Irrawaddy River in the central part of the basin. Another important tributary is the Shweli River that flows from the northeastern side of the basin and joins the Irrawaddy River further upstream from the confluence with Chindwin River. In the southern part of Myanmar, the main river channel branches into several courses, forming an extensive delta system. The Irrawaddy provides the main means of communication between important points in the interior and the southern port cities, especially Yangon (formerly known as Rangoon). The total drainage area of the Irrawaddy River Basin is approximately 387,700 km^2 (Fig. 3) with a population of about 30 million (Table 1).

2.4. Water use in the Himalayan River Basins

Traditionally, surface water from ponds and rivers had been used to provide both drinking and irrigation water supplies in all south Asian countries. However, over the last few decades, groundwater has largely replaced surface water-fed water supplies, especially for drinking water. Groundwater-fed irrigation in Bhutan and Sri Lanka is negligible compared to their close neighbours – Bangladesh and India. In Bangladesh, currently 97% of drinking and nearly 80% of irrigation water supplies come from groundwater (Fig. 2). At present, the use of groundwater for the dry-season irrigation in India, Pakistan, Nepal and Myanmar is approximately 60, 35, 19% and 9% of the total withdrawal of freshwater. By volume, India is the largest groundwater user in the world. A recent estimate shows that in India, Bangladesh, Pakistan and Nepal combined, the annual groundwater withdrawal is nearly 250 km^3 – approximately 35% of the world's total groundwater withdrawal. A substantial proportion of this groundwater is used to produce rice, the staple food in many south Asian countries. Recently, Bangladesh has made significant progress towards becoming a self-sufficient nation in food grains, primarily sustained through groundwater-irrigated agriculture [19].

3. Hydrology and Terrestrial Water Storage (TWS) Dynamics

Hydrological characteristics and terrestrial water storage variations over the Himalayan river basins are very dynamic due to the strong influence of the Asian summer monsoon climate and the shifting of the Intertropical Convergence Zone (ITCZ) through the seasons. The climate is characterised by heavy rainfall during the monsoon season but little during the dry season. A detailed description of precipitation and changes in terrestrial water storage – both seasonal and long-term are provided below.

3.1. Hydroclimatic characteristics

The distribution of rainfall in the Himalayan River Basins is highly seasonal due to variations in surface elevation (i.e. orographic effect), distance from the sea, and the location of the Himalayan Mountains with respect to the basins in general. The Indus River Basin is generally characterised by an arid to semi-arid climatic condition with varying rainfall [8]. On the plains, the climate varies from semi-arid to temperate sub-humid, whereas it is mostly alpine in the mountainous part of the basin in the north. Overall, the upper part of the basin (northern part) receives more precipitation than the lower part (southern) and plays an important role in surface water availability in the whole basin throughout the year. In contrast, the hydroclimatology of the GBM River Basin is characterised by a humid, sub-tropical climate with a unimodal distribution of annual rainfall that is strongly shaped by the Asian summer monsoon between June and September, over which ~80% of the annual rainfall occurs [20,31]. The Irrawaddy River Basin is also characterised primarily by a sub-tropical climatic condition. The lower part of the basin has a humid sub-tropical climate; the upper part has a warm, humid sub-tropical climate, and the middle part is characterised by a tropical dry zone. Both climatic zones are dominated by the Asian summer monsoon that brings heavy rainfalls between May and October.

Mean annual rainfall over a period of 12 years (2003–2014) shows spatial variations in annual rainfall over the various river basins in the Himalayas (Fig. 4). In this study, gridded (0.25 degree resolution), monthly rainfall data were extracted and processed over the Himalayan river basins from the TRMM (Tropical Rainfall Measuring Mission) satellite observations. The TRMM satellite mission ended in April 2015; it was a successful joint mission between NASA and the Japan Aerospace Exploration (JAXA) Agency to study rainfall for weather and climate research. The satellite was launched in late November 1997 with a design lifetime of 3 years; however, the TRMM satellite produced valuable scientific data over 17 years [22,23]. The TRMM satellite mission has already been superseded by an international satellite mission – the Global Precipitation Mission (GPM) that will provide next-generation observations of rain and snow worldwide every three hours. NASA and JAXA launched the GPM Core Observatory satellite in February 2014 to measure precipitation from space [23]. Note that GPM data are not used in this study.

Mean annual rainfall (2003–2014) over the Himalayan River Basins varies among each other as well as within basins themselves. For instance, the mean annual rainfall over the Indus River Basin varies spatially from 130 to 1380 mm/year. Mean annual rainfall over the Ganges River Basin ranges spatially from 330 to 3200 mm/year. Mean annual rainfall ranges spatially from 310 to 4800 mm/year, and from 1600 to 4800 mm/year, and from 900 to 3700 mm/year over the Brahmaputra, Meghna and Irrawaddy River Basins respectively. Although smallest in size, the Meghna River Basin is the wettest river basin in the Himalayan region. In contrast, the Indus River Basin is the driest in the region. Substantial spatial variations in annual rainfall are observed within each of these river basins in the Himalayan region (Fig. 5). For instance, the seasonal and spatial rainfall patterns of the Irrawaddy River Basin are dominated by the southwest monsoon. According to records of rainfall from 1988 to 1997 from the Department of Meteorology and Hydrology of Myanmar, 92% of the annual rainfall occurs during the southwest monsoon between May and October. The middle part of the basin called the Central Dry Zone lies in the rain shadow of the Rakhine Mountains, receiving an average annual rainfall ranging from 600 to 800 mm. The annual rainfall then progressively increases both upstream and downstream away from the dry zone ranging from about 4000 mm in the north to 2500 mm in the south [24].

Due to variations in regional climate and rainfall distribution as well as catchment area, the flow through major Himalayan rivers is highly seasonal and also varies substantially. The annual flow of the Brahmaputra River from China to India is approximately 165 km^3 and from Bhutan to India is 78 km^3. The combined annual flow of the Brahmaputra River from India into Bangladesh is 537 km^3 [8]. The annual flow of the Ganges River from China to Nepal is 12 km^3. All river channels in Nepal ultimately drain into the Ganges River with an annual flow of 210 km^3 to India. The combined annual flow of the Ganges River from India into Bangladesh is 525 km^3, which is comparable to the annual flow of the Brahmaputra River into Bangladesh. Annual river discharge of the Ganga-Brahmaputra river system greatly varies with season, with maximum values generally occurring in August–September and shows large year-to-year variations in the peak magnitude. For instance, for the period of 1993–2011, the mean aggregate discharge rate was estimated to be around 32,000 m^3/s. The annual maximum discharge rate has a mean value of ~82,000 m^3/s and a standard deviation of 14,000 m^3/s estimated over the same period [25]. In contrast, river discharge through the Meghna River is much lower than that of the Ganges and Brahmaputra Rivers. The annual flow of the Meghna River from India to Bangladesh is 48 km^3. So the total annual flow through the GBM River Basin from India into Bangladesh is approximately 1110 km^3. The combined discharge of the Ganges, Brahmaputra and Meghna Rivers is among the highest in the world. Average peak discharges are 100,000 m^3/s in the Brahmaputra, 75,000 m^3/s in the Ganges, 20,000 m^3/s in the upper Meghna and 160,000 m^3/s in the lower Meghna [15].

Annual flow from China to India in the Indus River is approximately 180 km^3 and it is estimated that the flow generated within India is 50 km^3, resulting in a flow from India to Pakistan of 230 km^3 in this part. The total inflow from Afghanistan to Pakistan in the Indus basin is estimated at 22 km^3. Annual discharge in the Indus River varies from place to place with an average discharge of approximately 7610 m^3/s [26].

Discharge rate through the Irrawaddy River varies from the headwaters in the eastern Himalayas and Tibetan Plateau from about 2000 m^3/s to an average 13,000 m^3/s in the south where the river empties to the Andaman Sea. Discharge is highest (average 35,000 m^3/s) during the monsoon season and lowest (average 4000 m^3/s) in the dry season, reflecting the seasonal variation in rainfall with the peak rainy season in August and September and dry winter season from January to April [24]. The estimated annual average discharge volume is 410 km^3/year based on data collected from gauging sites in the middle and lower sections of the Irrawaddy River [24].

3.2. A review of recent changes in GRACE-TWS

Evaluation of the spatio-temporal changes in TWS is critical for better understanding of the global and regional-scale hydrological cycles and water budgets. TWS variations over the Himalayan river basins are substantial both seasonally and spatially, which affect annual hydrological budgets and thus livelihoods of millions of people who depend on the availability of water supplies for irrigation and other agricultural, domestic and industrial activities. Monitoring and mapping of TWS variations over an area of interest require information on all water layers from land surface to subsurface (i.e., aquifer) stores,

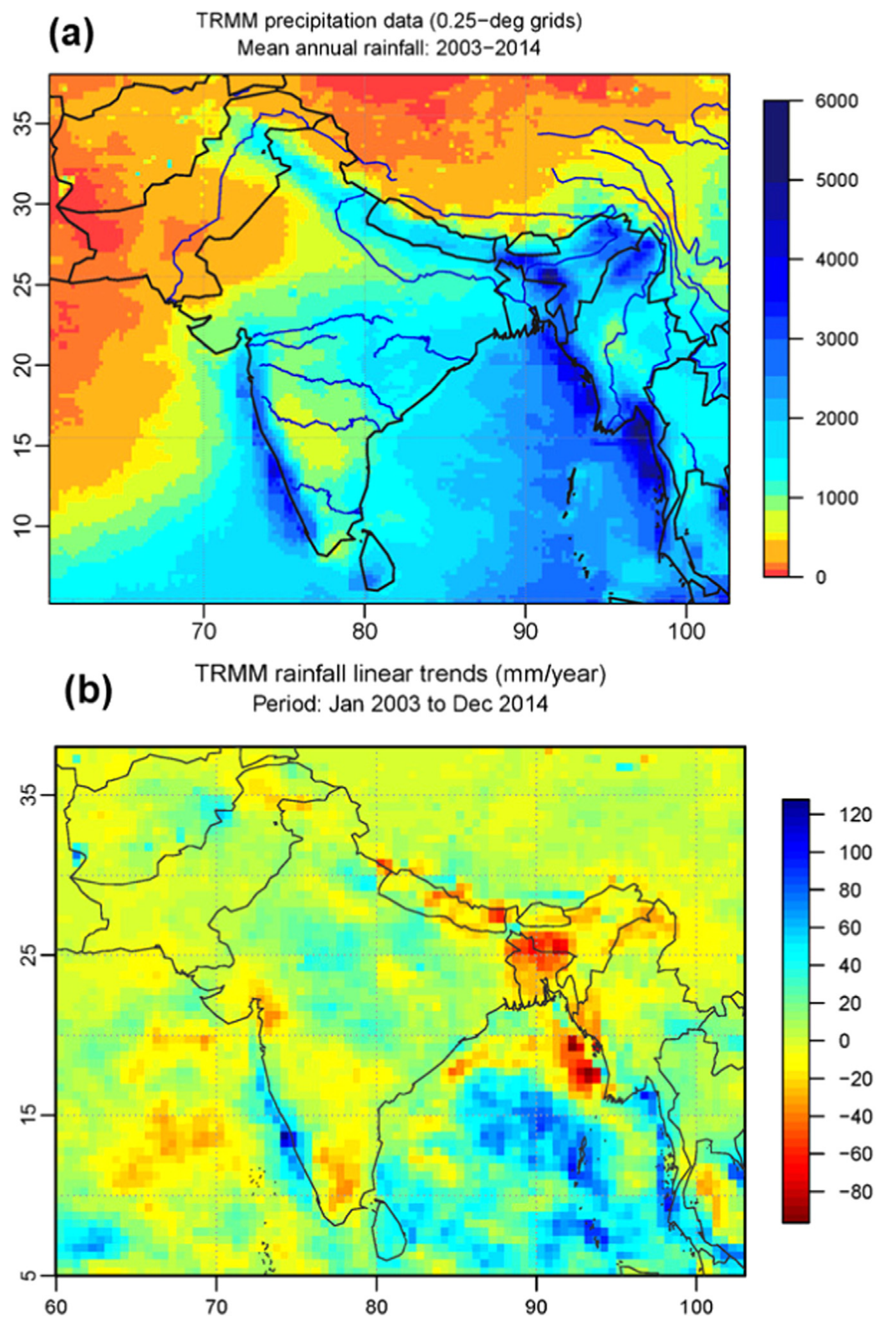

Fig. 4. Long-term (2003–2014) mean (mm) **(a)** and linear trends (mm/year) **(b)** in monthly precipitation estimated from satellite measurements under the Tropical Rainfall Measuring Mission (TRMM) jointly administered by NASA and the Japan Aerospace Exploration [22].

including surface water (i.e. river and seasonal flood water), soil moisture and groundwater. Monitoring of individual water stores in the Himalayan River Basins varies spatially and does not include all three water stores – surface water, soil moisture, and groundwater. Monitoring of surface water (i.e. river stage records) and groundwater levels is in place over most parts of Bangladesh, India and Pakistan that include the Indus and GBM River Basins. However, monitoring in water stores in the Irrawaddy River Basin is very limited and over most part of the basin no monitoring network exists. Lack of monitoring of water in the individual stores makes it impossible to map spatio-temporal variations in TWS over the Himalayan river basins using ground-based observations.

Recently, satellite monitoring of Earth's gravitational field by a pair of satellites under the GRACE (Gravity Recovery and Climate Experiment) satellite mission makes it possible to map TWS variations over the entire globe at 10-days to a monthly timescale since early 2002. The GRACE mission has been successfully conducted and funded jointly by NASA and DLR (German Aerospace Centre) under the NASA's Earth System Science Pathfinder Programme [27]. The GRACE consists of two identical spacecraft (satellites) that fly about 220 km apart in a polar orbit and 500 km above the Earth surface. The GRACE satellites map Earth's gravity field with unprecedented accuracy by making accurate measurements of the distance between the two satellites, using Global Positioning System (GPS) and a microwave ranging system [27]. The first GRACE satellite mission ended in late 2017 but a second, GRACE Follow-On (FO) mission has begun in May 2018 that will continue to measure the Earth's gravity field and thus movement of terrestrial water at the global scale [28].

The observational data from the GRACE mission have yielded crucial information about the distribution of TWS within Earth's surface

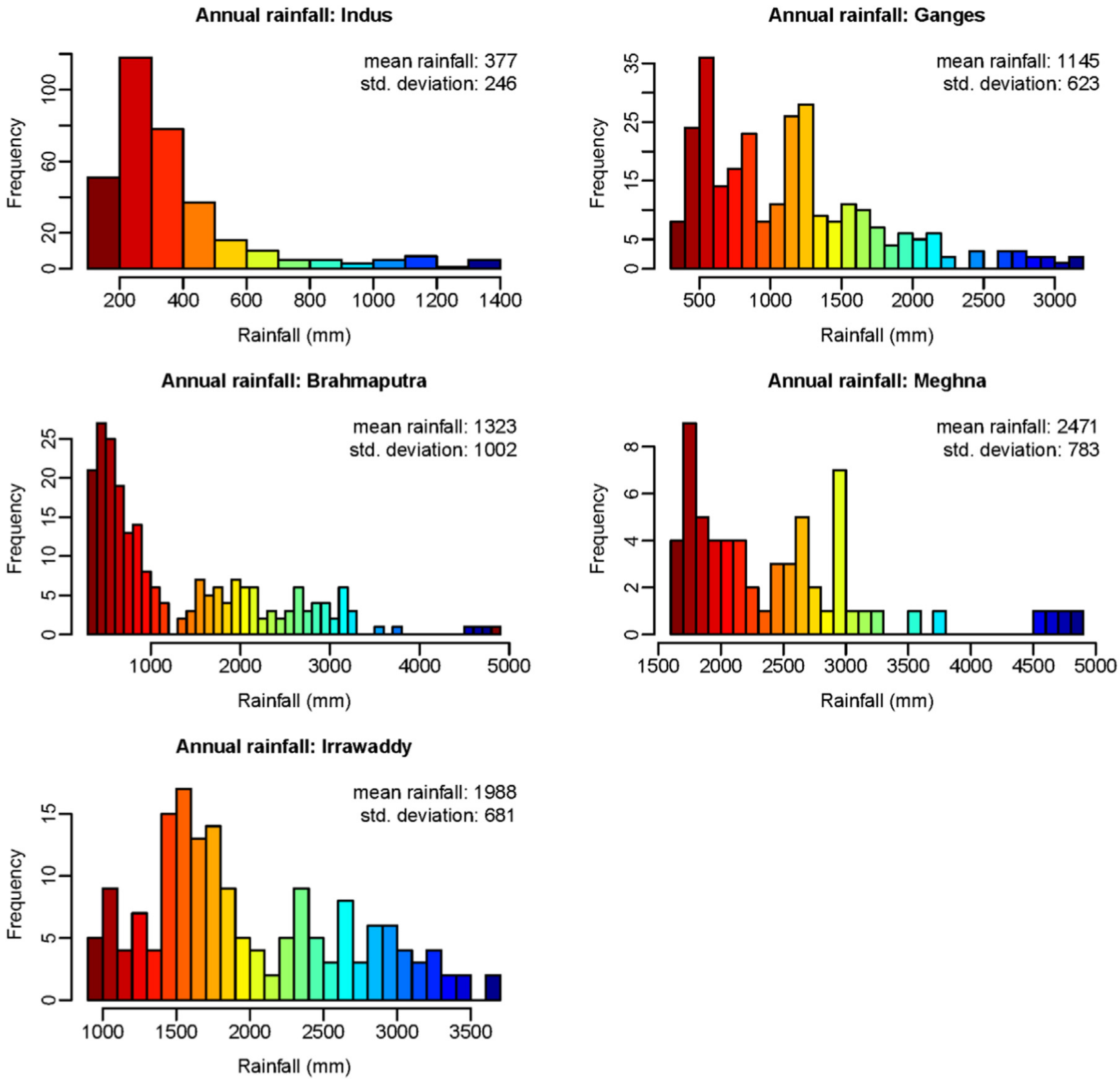

Fig. 5. Distribution of long-term (2003–2014) mean annual rainfall (mm) within the grid cells estimated from TRMM satellite measurements over each of the five major river basins in the Himalayan region. Mean values at individual grids are aggregated by several bin sizes. These bar diagrams illustrate how rainfall varies spatially in each river basin.

and near subsurface environments around the world. TWS variations within the Himalayan River Basins are particularly critical as water resources are vital for growing foods to feed nearly one billion people in the region. A number of studies on GRACE-derived observations of TWS anomalies over the Himalayan River Basins have been conducted over the last 10 years, of which assessing the spatio-temporal changes in groundwater storage (GWS) has been the main focus [3,4,9,10,12,21,29–33]. On the regional scale, GRACE observations for the period of 2003–2014 have revealed, for the first time, the dynamic seasonality in TWS variations due to climate and anthropogenic impacts. Monthly plots of TWS anomalies (Fig. 6) show that TWS varies substantially on a monthly basis, with April being, hydrologically, the driest and September being the wettest month. The greatest fluctuations in monthly TWS anomalies are observed over the GBM Basin where the range in average annual amplitudes can be as high as 400–500 mm. Seasonal variations in TWS anomalies over the Irrawaddy River Basin are similar to that of the GBM Basin but show slightly smaller fluctuations between dry and wet seasons. Monthly variations in TWS are smallest in the Indus River Basin where annual rainfall is also the lowest (130–1380 mm/year) of all Himalayan river basins.

Temporal trends in GRACE-derived TWS at the basin scale can be either linear or nonlinear as seasonality or episodic events (e.g. extreme precipitation) can dominate over the trend component in time-series data [34,35]. Here, we present linear trends (2003–2014) in mean monthly TWS anomalies in south Asia that reveal prominent declining trends (> 10 mm/year) over the Indo-Gangetic Plain, particularly in the Ganges and Brahmaputra River Basins (Fig. 7). Declining trends in TWS are only observed over the central part of the Indus River Basin that extends further northeast into Afghanistan and beyond. These declining trends are thought to be associated with substantial depletion of groundwater storage as the mass loss due to melting of the Himalayan glaciers in small [4,28]. Long-term trends in TWS anomalies over the Irrawaddy River Basin however show a positive change over time where TWS seems to have increased due to the accumulation of terrestrial water in the wet season. Interestingly, the south-central part of India, particularly the Godavari and Krishna River Basins, show a positive trend (> 10 mm/year) in long-term monthly TWS anomalies. These positive trends in GRACE TWS are attributed to increased long-term precipitation in the southern India [36].

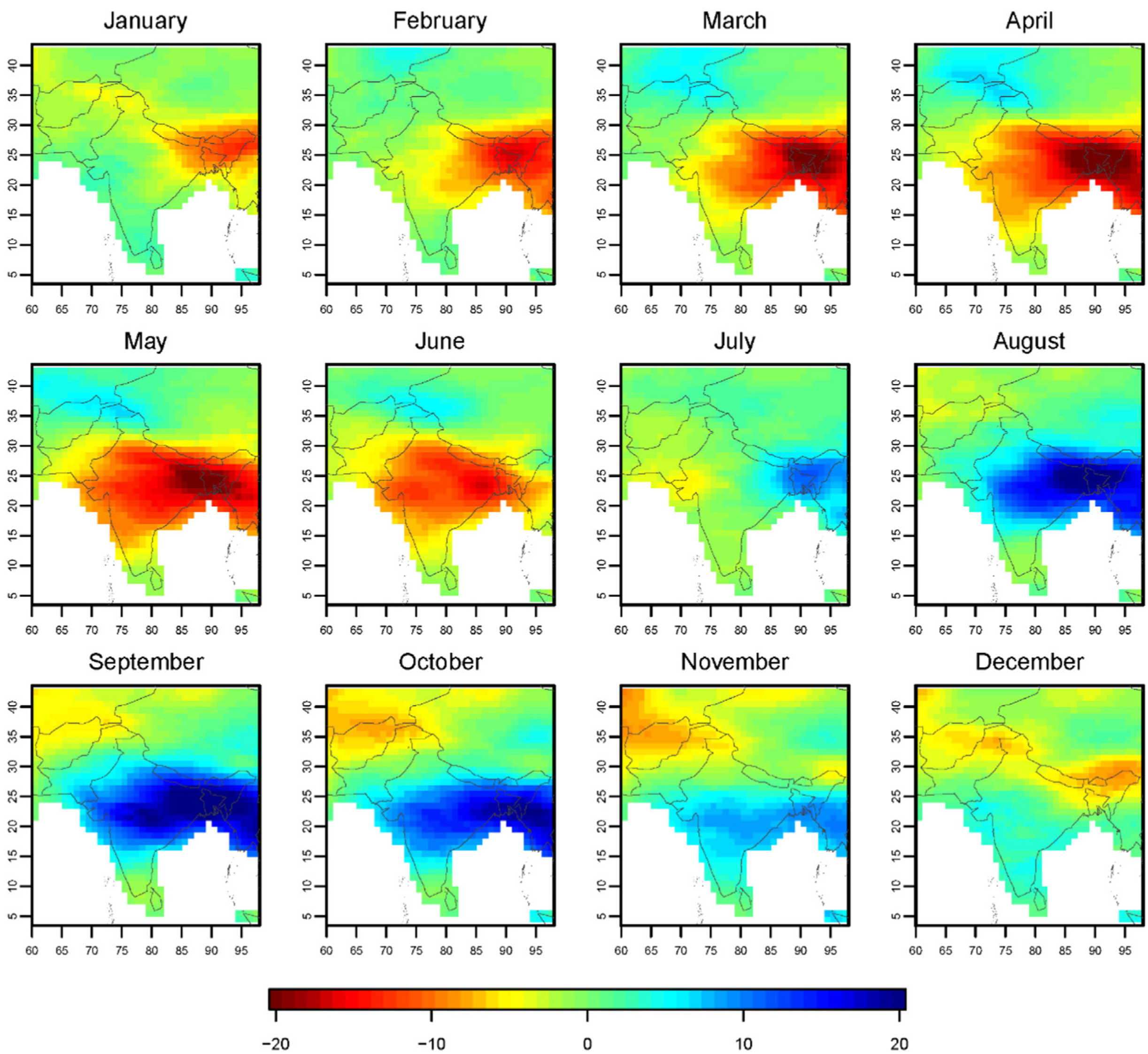

Fig. 6. Monthly variations in GRACE-derived terrestrial water storage (TWS) anomalies in south Asia. These monthly maps illustrate substantial spatial variations: high (> 10 cm) positive anomalies are observed over much of the Ganges-Brahmaputra-Meghna and the Irrawaddy River basins during the late monsoon season (Aug-Sep-Oct), and in the peak dry season (Mar-Apr-May), TWS values are completely opposite, indicating substantial annual fluctuations in the GRACE-derived TWS anomalies (data source: Centre for Space Research (CSR), University of Texas, USA).

3.3. *A review of recent changes in groundwater storage*

Due to lack of adequate and long-term monitoring of groundwater levels in the Himalayan river basins, the spatio-temporal changes in groundwater storage (GWS) have not been mapped at the basin scale. However, recently, a number of studies [4,10,31] have reported declining trends in groundwater storage over the GBM River Basin and, particularly over the northwest (NW) of India (Punjab, Haryana and Rajasthan states) where the GRACE satellites depict a very strong negative signal in the time-series (2003–2014) records of TWS anomalies (Fig. 7). In theory, GWS can be calculated from GRACE-TWS time-series observations as groundwater storage is a major component of the total terrestrial water storage. If changes in other water stores over time such as surface water storage (SWS), ice and snow water storage (ISS) and soil moisture storage (SMS) are known, GWS can be disaggregated from the GRACE-derived TWS time-series data (Fig. 8) as GWS = TWS–(SWS + ISS + SMS). One of the main challenges is that time-series records of SWS, ISS and SMS are often not available as these individual water stores are not even monitored in many parts of the world. Consequently, in almost all GRACE studies, the information on these auxiliary water stores is derived from global-scale land surface models (LSMs) and/or global hydrological models (GHMs) that are often not calibrated against observational records and poorly represent subsurface water stores including groundwater storage [12].

A series of studies [4,10,21,31] on changes in ΔGWS over NW of India employed GRACE-derived TWS and information on auxiliary water storage from simulated LSMs and/or GHMs and reported that GWS has declined substantially in the last decade. For instance, Rodell et al. [10] reported a loss of 4.0 ± 1.0 cm /year (equivalent volume of water 17.7 ± 4.5 km^3/year) over the Indian states of Rajasthan, Punjab and Haryana (including Delhi) for the period of August 2002 to October 2008. Another study [4] encompassing the entire Indo-Gangetic Plain and part of the Himalayan Mountains reported a total water-mass loss of 54 ± 9 km^3/year and they attributed the entire rate to GWS loss. These estimates further suggested that the volumetric groundwater-loss rate over the Ganga-Brahmaputra Basin was equivalent volume of 34 km^3/year compared to ~10 km^3/year over the Indus River Basin and ~10 km^3/year over western Pakistan and mountainous areas in Afghanistan. Yet another GRACE-based study in India [31] reports a total groundwater storage loss at a rate of 20.0 ± 7.1 km^3/

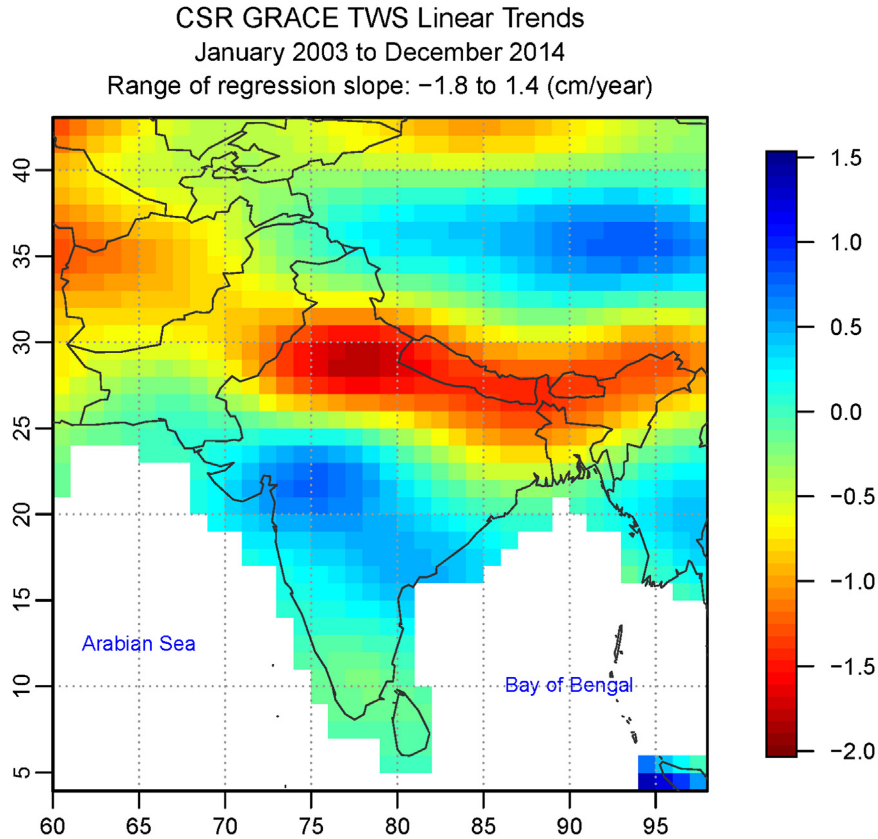

Fig. 7. Long-term (2003–2014) linear trends in the monthly CSR GRACE-derived TWS anomalies in southern Asia. Strong negative trends (–1–2 cm/year) are observed in the Indo-Gangetic Basin covering much of the Indus and GBM River basins.

year over a 10-year period (January 2003 – December 2012). Using both GRACE and in-situ groundwater-level time-series records Panda and Wahr [21] report that GRACE-derived GWS loss over the Ganges River Basin is at a rate of 1.25 cm/year. Recently, a study [33] evaluates GWS loss over NW of India using GRACE-derived TWS and ancillary information from LSM/GHM and reports that GWS has declined at a rate of 3.1 ± 0.1 cm/year (equivalent volume of water 14 ± 0.4 km^3/year) for the period of January 2005 to December 2010 that is consistent with the GWS loss of 2.8 cm/year (12.3 km^3/year) based on estimates from observations through a groundwater-level monitoring network. Using in-situ groundwater-level observations over the entire Indo-Gangetic Basin (IGB) alluvial aquifer system, a recent study [9] reports a net mean annual groundwater depletion at a rate of 8.0 km^3/year (range 4.7–11.0 km^3/year) over the IGB with significant variation observed across the basin over the period of 2000–2012. According to this study, the largest depletion of groundwater storage occurred in areas of high abstraction and consumptive use in northern India (Punjab State 2.6 ± 0.9 km^3/year, Haryana State 1.4 ± 0.5 km^3/year, and Uttar Pradesh State 1.2 ± 0.5 km^3/year) and Pakistan (Punjab Province 2.1 ± 0.8 km^3/year) [9]. In the Lower Indus, within the Sindh Province, groundwater is, however, accumulating at a rate of 0.3 ± 0.15 km^3/year, which has led to increased waterlogging of land and substantial reduction in the outflow from the River Indus. Across the rest of the IGB, changes in groundwater storage are generally modest (within ± 1 cm/year). Time-series records of seasonally monitored boreholes from the Ganges River Basin reveal that the long-term dry-season levels have declined but substantial variation is observed during the wet season [21].

4. Concluding discussion

Spatial and temporal changes in the terrestrial water storage (TWS) in the Himalayan river basins in South and Southeast Asia have been a focus of many recent studies that primarily depend on remote-sensing data such as GRACE gravity observations to map trends in TWS and its critical components such as groundwater storage (GWS). Auxiliary information on soil moisture storage in disaggregating GRACE-derived TWS for GWS comes primarily from global-scale land surface models that are rarely calibrated with any ground-based observations. A very few studies [9,12,21] have reported changes in GWS using in-situ monitoring records from borehole networks exist in some Himalayan river basins (e.g. Ganges, Indus and GBM basins). Although GRACE satellite-derived changes in TWS compare appreciably with in-situ observations at the basin scale (> 100 s of km), substantial small-scale (10–100 s of km) variations exist in various components of TWS. This is critical to understand for water management and policy development as groundwater-fed irrigation in the Himalayan region is predominantly small-scale and managed by smallholder farmers. Contribution of monsoonal floodwater and surface water storage to TWS is critical in the Himalayan river basins that experience great variability in the available surface water through various seasons.

Development of groundwater resources for drinking in the Himalayan river basins is remarkable. However, use of groundwater for dry-season irrigation is not evenly distributed within various river basins. Groundwater use in Bangladesh, India and Pakistan has been substantial over the last several decades. Groundwater use is, however, not yet fully developed in Bhutan, Nepal, Myanmar and Sri Lanka where it would be critical in order to meet future demand for food and safe drinking water for a growing population. At the same time, there are lessons to be learned of adverse consequences of excessive withdrawal of groundwater and surface water for irrigated agriculture in Bangladesh, India and Pakistan that resulted under the so-called ‘Green Revolution’ [37].

A sustainable public and irrigation water supply is essential for

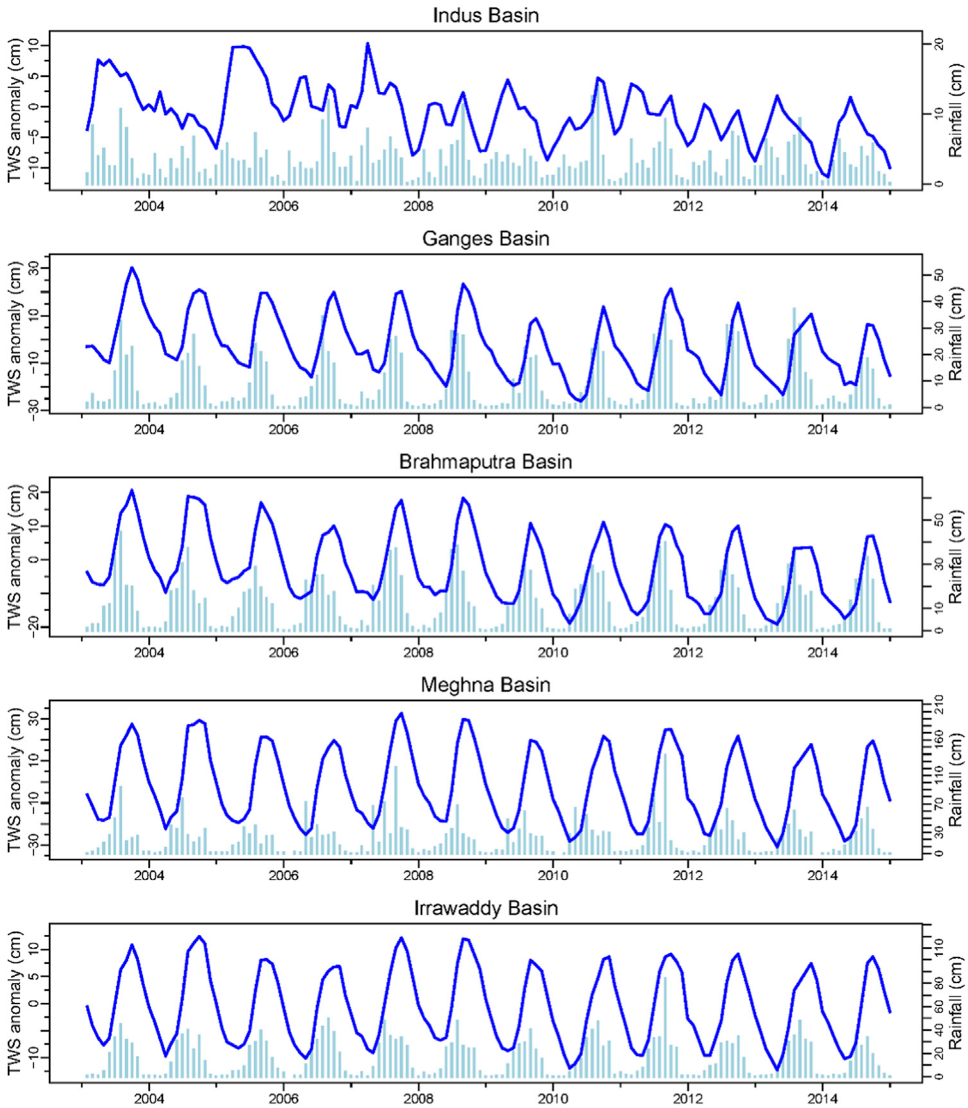

Fig. 8. Monthly time-series (2003–2014) records of the CSR GRACE-derived TWS anomalies for the five river basins in the southern Asia. Monthly TWS data are averaged over the respective river basin to produce a time series (shown in thick blue line); monthly rainfall records from CRU dataset (Climatic Research Unit, University of East Anglia, UK) are extracted and processed for each river basin (shown as bars in light blue lines).

improving health, and achieving economic growth and food security in the Himalayan region and elsewhere around the world. Currently, the key groundwater resource in the Himalayan region is facing great challenges due to overall deterioration in quality and decline in quantity (long-term storage) resulting from a range of issues including natural (e.g., arsenic, salinity) and anthropogenic contamination, land-use change (e.g., urbanisation), over-abstraction, mismanagement and poor governance [9]. Critically, the strategic importance of groundwater resources for global water and food security will further intensify under human development, and global warming and climate change [13].

Acknowledgements

We kindly acknowledge NASA's MEaSUREs Program for providing GRACE land solutions and the Goddard Earth Sciences Data and Information Services Center (GES DISC) Mirador search tool for providing the Tropical Rainfall Measuring Mission (TRMM) monthly rainfall data (3B43 version 7). We acknowledge the support from Bangladesh Water Development Board (BWDB) and the Indian Central Ground Water Board (CGWB) for providing groundwater-level monitoring records. LandScan global population data and FAO AQUASTAT data are duly acknowledged. We thank the Institute for Risk and Disaster Reduction (IRDR), University College London, the Geological Society of London (UK), and the Institute of Energy Research & Training at University of Jammu (India) for their kind support that enabled the lead author to attend an international workshop 'Sustainable Resource Development in the Himalaya' in June 2014. Finally, we acknowledge support from NERC-ESRC-DFID UPGro '*GroFutures*' (Ref. NE/M008932/1; www.grofutures.org), and DFID funded project, 'Indo-Gangetic Basin Groundwater Resilience' (Ref. 202125-108).

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